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Frequency Stabilizing Scheme for a Danish Island Grid

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***Abstract*--This paper describes the development of frequency stabilizing control scheme for a small Danish island of Bornholm. The Bornholm power system is able to transit from interconnected operation with the Nordic power system to isolated islanding operation. During islanding operation the shedding of wind power is necessary to avoid unwanted power oscillations, which lead to uncontrolled oscillations in the power plant control. Since this might deteriorate power quality including frequency in an island grid, a frequency stabilizing control scheme or strategies using intelligent controller with a battery energy storage system (BESS) has been proposed. The real-time models of distribution grids of Bornholm power system were used to carry out case studies to illustrate the performance of centralized load frequency control as well as coordinated control scheme. Case study results show that the proposed coordinated control scheme can efficiently help stabilize the frequency after switching to islanding operation.**

***Index Terms*—Battery energy storage system (BESS), Danish island grid, islanding operation, load frequency control (LFC), real time digital simulator (RTDS)**

I. Introduction

DENMARK has a very pro-active energy policy. As it can be seen in the future energy outlook and policy of Denmark, more renewable energy integration is planned in near future. The Danish parliament has entered a new energy agreement and set a target of 50% penetration of wind power in 2020 and 100% penetration renewable energy in 2035 [1]. The central power plant units will be reduced to 4,100 MW which will be restricted to 57% of the current installed capacity. Also, energy strategy 2035 is a huge step towards realizing Danish government's vision of becoming independent of coal, oil and gas. The political objective is 100% independence of fossil in the long term [2]. In regards to the future energy system, Bornholm is in the center of attention in most of Europe and some parts of the world due to the characteristics of the Bornholm power system and ongoing large demonstration projects of smart grid on Bornholm. Bornholm is a small Danish island on the outskirts of eastern Denmark in the Baltic sea, which is situated just south of Sweden. Since, Bornholm already has a high share of electricity supplied by renewable energies (i.e PV, Biomass, etc), particularly wind power, its system can be highly regarded as a future power system. The electric power system on Bornholm is a distribution network consisting of three voltage levels: 60kV, 10kV and 0.4kV. The peak load in Bornholm is between 50MW and 63MW while the minimum load is between 13MW and 18MW. The power generation in the Bornholm power system contains 14 diesel units, 1 steam unit, 1 combined heat and power (CHP) unit, biomass and a large share of wind turbines exceeding 30% of total energy consumption with an additional 20MW estimated to be installed in the near future. The wind turbines are situated all over the island and are mainly dominated by onshore wind turbines. This future scenario of increased capacity of wind power will certainly raise serious challenges to the power system operation and control. Additional power balancing is required to deal with the intermittent characteristics of the wind power.

Moreover, from the 135kV substation TOMLILLA, there is an overhead line connected to 135 kV substation, BORRBY. The 60kV side of the transformer (BOR135-BOR60) in the BORRBY substation is connected to the 60kV substation HALSE, Bornholm by the mixture of overhead lines and AC submarine cables (total length of 49.8 km). There are 16 substations, 23 OLTC transformers, and 22 cables / 26 overhead lines in this region. The sea cable can be disconnected which gives the opportunity to test in a restricted area with a very high amount of renewables. During these periods, frequency control of the system became fairly difficult. Several projects in Denmark have been investigated by Energinet.dk, the transmission system operator (TSO) [3-5]. During this particular project [5], a newly developed real time model for Bornholm power system using real time digital simulator is conducted as part of PowerLabDK phase I. Such a situation demands for more efficient frequency and voltage regulation. In order to handle the challenging issues during islanding operation, the system performance during this islanding transition should be thoroughly analysed and a proper frequency stabilizing control scheme for the island grid and an accurate model of thermal and CHP units including governors are vital. Furthermore, the PowerLabDK is an internationally unique experimental platform for sustainable electric power and energy systems. It is one of Europe's most advanced research site for development and demonstration with distributed control architectures for large-scale power systems, coupled with a state-of-the-art control room with a full scale SCADA system. The platform can be used to investigate all aspects of the challenges and requirements of future power systems related to operation and control. PowerLabDK can be used ranging from basic research to large-scale, and full-scale experiments with the Bornholm

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power system which has more than 28,000 consumers and more than 33% wind power penetration [6].

Electrical energy in an ac system cannot be stored, and must typically be generated and consumed at the same time. However, energy can be stored by converting the ac electricity and storing it in different mediums as potential energy [7]. The need for storage devices and their utilization in power systems has long been debated. Some of the literature discuss about the various storage technologies mainly such as superconducting magnetic energy storage (SMES), advanced capacitors, flywheel, and batteries, and suggest that so far the battery technology in commercial use today is the most widely used storage device for power system applications [8–10]. Further, it is also stated that the energy storage technology will be the key to the future development of renewable energy scenario as previously mentioned. In this section, only the BESS concept is briefly discussed. The examples adopted in this section are based on the previous author's earlier reviews on the power system study time scale [11]. In [12] the focus has been made to quantify the technical benefits of using a 30 MW BESS in an isolated power system for providing frequency regulation. For this purpose, the frequency variance of an isolated Israel system with and without BESS has been calculated for a measured load disturbance. The modelling and data requirements for BESS for power system stability studies have been discussed in [13]. These BESS models have been implemented in the TSAT, SSAT, and VSAT. Integration of the BESS technology with flexible ac transmission systems (FACTS) and custom power devices are among the possible power applications utilizing energy storage which can improve the power system operation and control. In [14] a dynamic model of BESS expressed as a transfer function blocks for large scale power system studies has been suggested. This model is developed by combining the equivalent circuit model with the available battery model. For this purpose, the dynamic responses of the system with and without the BESS have been evaluated. During the dynamic period, the BESS can draw active and reactive power from the power system or discharging to the grid according to the system requirement. One of the recent investigations [15] presents the cooperative control strategy of micro grid during islanded operation. For this purpose, a 120-kW micro grid pilot plant and micro grid management system were developed and tested with and without BESS under various operating conditions using the PSCAD/EMTDC simulation platform. The BESS application have recently emerged as one of the promising near-term storage technology and becomes significantly important in small or island power system with rather low spinning reserve, where the load variances have a considerable effect on the network frequency. Several large scale stationary BESS units have been designed and installed in existing electric utility grid applications for the purposes of short-term spinning reserve, primary frequency control, smoothing of power output from wind farms, active and reactive power control, load balancing, micro grid support. In this paper, a new centralized joint load frequency control (CJLFC) scheme has been developed to stabilize frequency for islanding operation of distribution networks. This control scheme utilizes distributed energy resources (DERs) including battery energy storage system (BESS) in the system to help stabilize the frequency after the networks enters into the islanding operation mode.

The Bornholm power system has been chosen for demonstrating the proposed frequency stabilizing control scheme.

The rest of the paper is organized as follows. The control strategy of BESS and CJLFC is presented in Section II. The Bornholm power system and BESS model are described in Section III. The case study results are presented in Section IV and a conclusion is drawn in Section V.

II. Control Strategies of BESS and CJLFC

The main concept for islanding operation involves the coordinated control of the BESS and other thermal units, as shown in Fig. 1.

A. *BESS Control*

1) During the grid-connected operation

The objectives of BESS are maintaining the grid frequency and the voltage within the permissible limits. In this operation, these tasks are mainly carried out by the external grid. Therefore, the BESS is not in active state.

2) During the islanded operation

The power generated by renewable energy sources varies faster than traditional power generation. If there is no BESS, the power balance between the generated power and the existing loads does not always match due to the renewable energy fluctuations. As a result, the frequency and the voltage of the grid will fluctuate. This must be synchronized or it can lead to grid instability under fluctuating frequency conditions. Once the islanded situation is detected, BESS is activated. Clearly, the BESS can provide fast response by proper power balancing as other thermal units have a relatively slow response time. Thus, the frequency and the voltage of the grid can be regulated at the nominal values. However, due to its capacity limitation, BESS should be coordinated with CJLFC. According to the proposed coordinated control scheme, the CJLFC detects the change in the power output of the BESS and assigns the difference to the thermal units. This secondary regulation control can reduce the consumption of the stored energy of BESS without degrading the control performance.

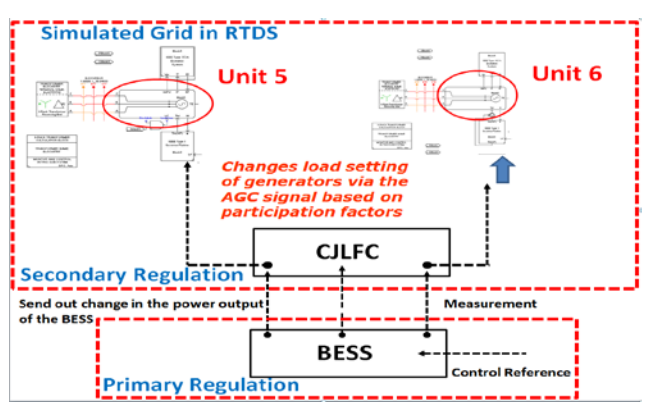


Fig. 1. Coordinated control scheme of BESS and CJLFC

B. *Centralized Joint Load Frequency Control*

A brief description on the modelling of CJLFC is provided in this section. The secondary load frequency control can be built in a number of ways, either locally or in a centralized and automatic way as represented in Fig. 2. The secondary load frequency control is performed as follows. If the system is operating in grid-connected mode, the centralized control is disabled. However, if the grid becomes isolated, then the centralized control must coordinate with BESS. The two main objectives of the secondary control are to keep the system frequency at or close to 50 Hz and to maintain each thermal unit's generation at the most economic value. The centralized join load frequency control is enabled subsequently to the action of local thermal unit's response to an imbalance between load and generation. This imbalance can be caused either by the islanding of the grid or by variations in load. In order to perform load frequency control, the centralized control receives and stores information from the load (load levels), thermal units (active power levels) and frequency measurements. Using above frequency deviation as input and based on their participation factors calculated using cost-functions associated with each thermal unit and economic set points. The secondary frequency control implemented in the centralized control specifies the active power set-points that are sent back to the thermal units in order to adjust the production levels and consequently correct the frequency offset. The centralized secondary load frequency control structure used in this work is based on the previous author's research [16], and is depicted in Fig. 2.

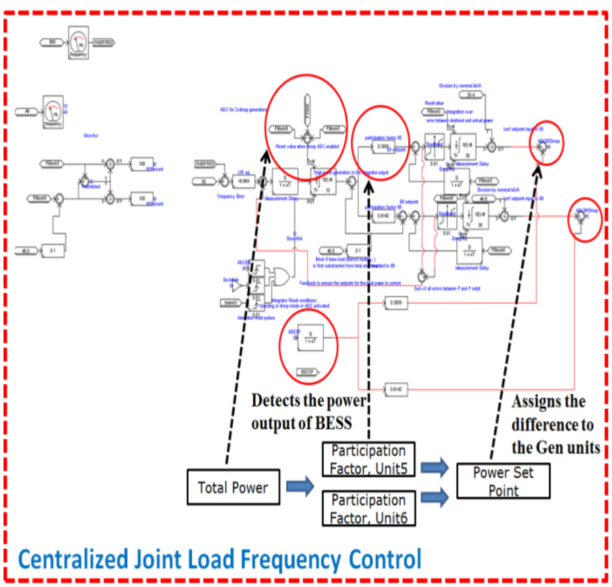


Fig. 2. Centralized joint load frequency control

In the CJLFC, the participation factors can be modified accordingly. For example, it can have all governors share a common load reference (relative to their rated MVA), and then adjust this common load reference, subsequent to a load change in order to restore the frequency to nominal. Or, it can be added to base loads and participation factors. Base load is the minimum load of a generation unit. It is useful if a coal power plant is used for district heating (CHP), it is then required to always supply enough hot water according to heat demand for the consumers, and thus should always generate a certain amount of power. Participation factors are the percentage of the system load (minus base load) that each of the generation unit is set to supply. For our simulation case, two thermal units where the unit 6 has a base load, their individual power contribution can be calculated as following:

Generation Unit 5:

$$P_{G5} = \left(P_{SYS} - P_{base,G6}\right) \cdot pf_{G5} \quad (1)$$

Generation Unit 6:

$$P_{G6} = \left(P_{SYS} - P_{base,G6}\right) \cdot pf_{G6} + P_{base,G6} \quad (2)$$

where, P_{sys} and $P_{base,G6}$ are the system total power and the base load of the unit 6 (rated MVA) respectively, pf_{G5} and pf_{G6} are the participation factors respectively.

The load reference of each thermal unit must then be set in order to reach nominal frequency:

$$L_{ref,G5} = \frac{(P_{SYS} - P_{base\ G6}) \cdot Pf_{G5}}{S_{rated,G5}} \quad (3)$$

$$L_{ref,G6} = \frac{(P_{SYS} - P_{base\ G6}) \cdot Pf_{G6} + P_{base\ G6}}{S_{rated,G6}} \quad (4)$$

where, $S_{rated,G5}$ and , $S_{rated,G6}$ are the rated MVA of the machines.

The CJLFC scheme, as shown in Fig. 2, measures the system frequency and changes load settings of thermal units via the LFC signal. The CJLFC calculates the average power that has to be distributed among the thermal units connected to the load frequency controller. The resultant control signal specifies the active power set points to the selected thermal units for power production adjustment based on participation factors, p_{f5}, p_{f6}, where the sum of the participating factors are equal to unity.

III. Bornholm Power System & Battery Model

The Bornholm power system and battery model are described in detail in this section.

A. *Bornholm Power System*

The Danish power system is electrically separated into two parts, the western part connected to the Union for the Coordination of Electricity Transmission (UCTE) system and the eastern part connected to the Nordic synchronous area. The island of Bornholm is part of the Nordic power system where the secondary control operation is manually operated. The Bornholm power system is connected through a long submarine cable to the Swedish power system, represented in the model as a simple external grid. The power system contains both 60kV and 10kV buses. A detailed description and the parameters can be found in [5]. The basic Bornholm model has been slightly modified and the final test system used in this simulation is depicted in Fig. 3. The real power system of Bornholm is used to illustrate the islanding operation of the distribution grid, and to validate the proposed control scheme. The Bornholm system also consists of an aggregated WPPs modeled jointly as a 2 MW generation unit plus battery energy storage system (BESS) from [17]. The WPP and BESS are connected to the grid at the point of common coupling to be utilized when the system transit into islanding operation. Both load and wind speed can also be modified in order to simulate a drop or increase in load demand & wind power production. Instead of an existing manual secondary control mode in Bornholm, an automatic load frequency control with the BESS regulation under islanded mode is analyzed.

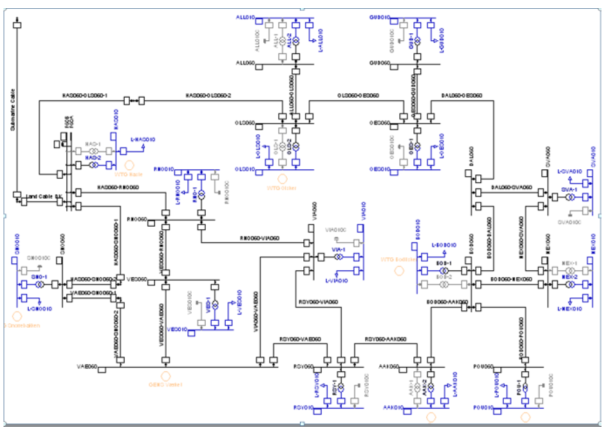


Fig. 3. Single-line diagram of detailed power system of Bornholm

B. *Battery Energy Storage System (BESS)*

The BESS enables smoothing of fluctuations for wind and solar generation units. The system provides a mechanism to store intermittent energy generation, which provides consistent power to the grid. Quick-response characteristic alleviates rapid shifts in renewable energy generation and can therefore act as a frequency regulator. In practice, the BESS consists of rectifier/inverter, battery cells and the Energy Storage System (EMS). The rectifier/inverter is normally based on a voltage source converter (VSC) and a pulse width modulation (PWM). It acts as the interface between DC and AC sides. If the converter losses, internal dynamics of battery cells and battery capacity are ignored, the battery can be regarded as the controlled current sources for three phases. This simplified model is depicted in Fig. 4 and implemented in this study. The EMS manages the active and reactive power exchange. There are different control objectives for EMS. Here, the tasks are stabilizing the grid frequency and voltage of the connected bus. Therefore, frequency and voltage are taken as the inputs to determine the active and reactive power references, which equate d and q components of the control signals for the current sources. Considering limitation of the battery power, the derived current control signals have upper and lower limits.

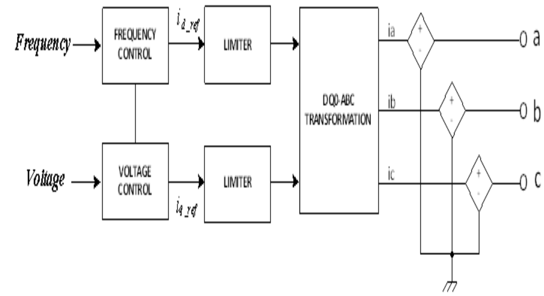


Fig. 4. Simplified BESS model

IV. Simulation Results

In order to assess the performance of the proposed coordinated control scheme, four simulation cases were performed. The frequency and voltage response is conducted with storage with an option of coordinated control on and off environment after switching to islanding operation as the first or reference case. The simulation with and without the BESS regulation, where two of the generators participate in the CJLFC is considered but no coordination is involved between the BESS and two generators. For the remaining simulation cases, two different scenarios are selected and analyzed. As a third case, the case is similar to the reference above. The wind speed variation is considered during islanding operation. Lastly, the frequency and voltage response is conducted by the load variations are considered. The initial condition for each case is that the load is balanced with the production at exactly 50 Hz. This system initially has about 21.8 MW load. The centralized control is continuously monitoring the voltage and frequency to respond to any disturbance. A 3-phase fault disconnecting from the utility grid is applied at the nominal operating conditions $(P_{scr} = 1pu,\ \delta_0 = 0, initial\ power\ flow\ of\ 1.57\ MW)$ at t = 9 sec.

A. *Case I*

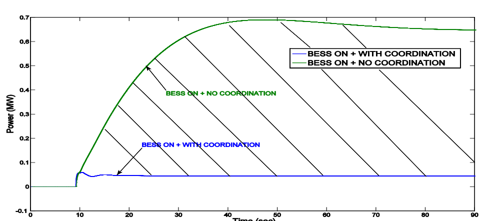
The simulation result of the first scenario is presented here, where two of the generators participate in the CJLFC during islanding operation mode. The scenario is characterized by a total load of 21.8 MW and the generation of two units 18.3 MW, wind 1.93 MW, and external grid supplying 1.57 MW. When the grid is disconnected and the BESS is activated with an option of CJLFC coordination on and off environment. The execution sequence is described as follows;

- Step 1. Utility grid fault apply
- Step 2. Observe frequency & voltage drop/rise
- Step 3. BESS activated as a primary control
- Step 4. CJLFC activated with and without coordination option as secondary control
- Step 5. Frequency & voltage recover

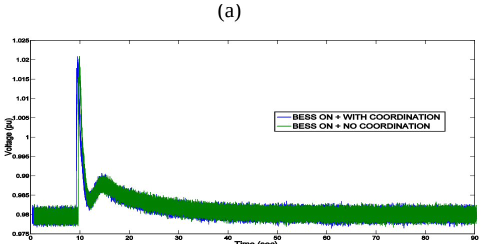
The main focus of this reference case is to explain the role of BESS and its coordinated control scheme with CJLFC. In Fig. 5(a), the power output of BESS changes from zero to a certain value in order to control the frequency and the voltages at the instant of disturbance as a primary regulation. During this islanding operation, the output power of two thermal units also changed from an initial values to a new power set points calculated by secondary control, as shown in the Fig. 2 in Section II. The CJLFC detects the change in the power output of the BESS and assigns the difference to the thermal units. This secondary regulation control can reduce the consumption of the stored energy of BESS without degrading the control performance. It is clearly observed that using only small amounts of BESS (i.e 0.045 MW) can improve the response of the Bornholm system in the Fig. 5(a, blue curves). The power BESS injects is shown with legend BESS ON + WITH COORDINATION (blue curves) and the power BESS injects without coordination control is shown with legend BESS ON + NO COORDINATION (green curves), respectively. As it can be seen from Fig. 5(a) that the reason for the fact that only 0.045 MW of BESS are requested in the event of islanding operation is that the other thermal units also provide frequency regulation and the BESS does not need to contribute or compensate the complete power mismatch. Hence, the regulation power requirement from the BESS is also greatly reduced with two other thermal units participating in load frequency control. The shaded area in the figure (below) represents the total power contributions from two thermal units.

In the Fig. 5(b), (c), the voltage and frequency response with BESS regulation control are shown with legend BESS ON + WITH COORDINATION (blue curves). Also, the voltage and frequency response with BESS regulation control are shown with legend BESS ON + NO COORDINATION (green curves), respectively. The power injections from two thermal units are represented in the Fig. 5(d) and 5(e).

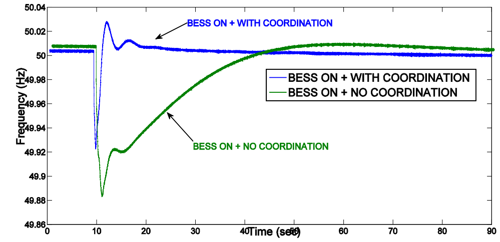
The operation control strategy is to use BESS as primary regulation and two other units for providing secondary frequency regulation. Moreover, Fig. 5 indicates that the BESS reacts fast and thus the system is able to reach steady-state operation.



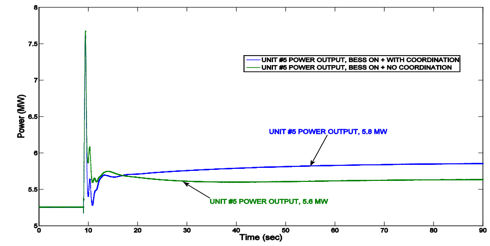
(a)



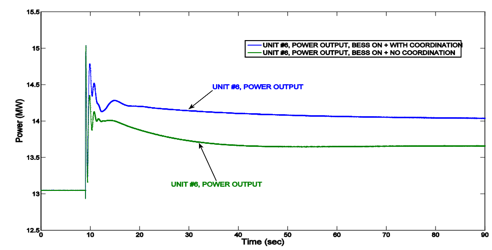
(b)



(c)



(d)



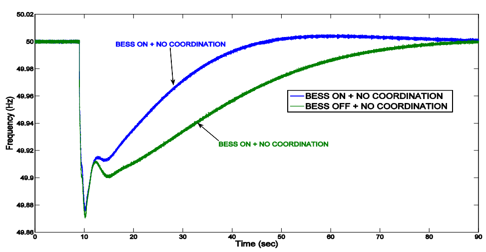
(e)

Fig. 5. BESS regulation & coordinated control on & off option (a) BESS P_{out}, (b) voltage, (c) frequency, (d) Unit #5 P_{out}, (e) Unit #6 P_{out}

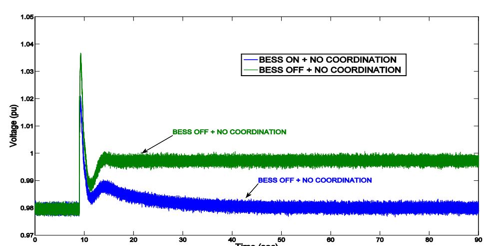
In addition, it is observed that the two generators are switched on to V-f mode after islanding to control the overall island voltage and frequency by sharing or rescheduling between two units based on the participation factors. The output powers of two generators increased from initial values to new values to consequently correct the frequency offset. As it can be seen from Fig. 5(c, blue curves) that the frequency dropped to 49.92 Hz and then recovered to the nominal value after 20 sec and settled again at 50 Hz. Due to its coordination control, the frequency is still kept in a very narrow range. The two intervals between times 10 sec to 30 sec show the contribution of the primary frequency control and the time intervals between 30 sec to 60 sec highlight the interests of the secondary frequency regulation. Overall, the five sets of results in the Fig. 5 show a good contribution of the islanded grid both for primary and secondary frequency control. The BESS ensures that the frequency remains within threshold limits of the power system as evident from the frequency response. In this case, the maximum frequency after islanding event was less severe with BESS ON + WITH COORDINATION than without coordination.

B. *Case II*

In this case, the frequency and voltage response is also conducted with and without the BESS regulation, where two of the thermal units participate in the CJLFC. However, the coordination control scheme between the BESS and the CJLFC is not considered during this islanding operation. In the Fig. 6(a), (b), the frequency and voltage response with BESS regulation control is shown with legend BESS ON + NO COORDINATION (blue curves). Also, the frequency and voltage response without BESS regulation control is shown with legend BESS OFF + NO COORDINATION (green curves), respectively. As it can be seen from Fig. 6(a, blue curves) that the frequency dropped to 49.88 Hz and then recovered to the nominal value after 55 sec and settled again at 50 Hz. Due to the absent of coordination control, the frequency is slowly recovered as opposed to the results obtained in reference case (i.e much faster). Nonetheless, the stability of the system is well maintained and the BESS can effectively stabilize the frequency and voltage of the system after switching to islanding operation. Thus, the BESS ensures that the frequency remains within threshold limits of the power system as evident from the frequency response. The power injections from two thermal units are represented in the Fig. 6(c) and 7(d). Furthermore, the four sets of results in the Fig. 6 show a good contribution of the islanded grid both for primary and secondary frequency control. The BESS ensures that the frequency remains within threshold limits of the power system as evident from the frequency response. As expected, the maximum frequency after islanding event was less severe with BESS ON + NO COORDINATION than without the BESS.



(a)



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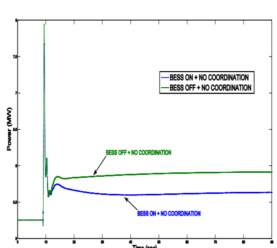
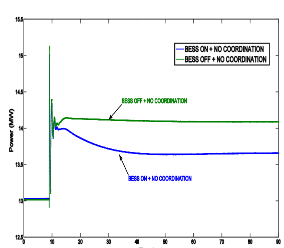


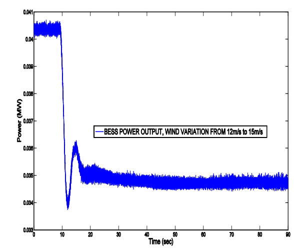


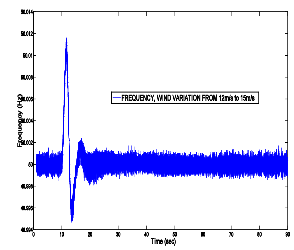
(c) (d)

Fig. 6. BESS regulation with and without no coordinated control (a) frequency, (b) voltage, (c) Unit #5 P_{out}, (d) Unit #6 P_{out}

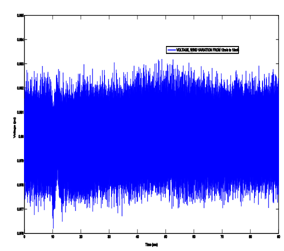
C. Case III

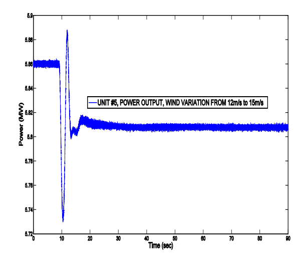
The results obtained with wind speed variation are presented in the next figures. In this particular case, the wind speed was modified from 12m/s to 15m/s while simulation in order to simulate an increase in wind power production as shown in Fig. 7 (f). The BESS ensures that the frequency and voltage remain within threshold limits of the power system during islanding operation as evident from the Fig. 7(b) and 7(c). Also, it is observed that the BESS reduced its output power from 0.045 MW to 0.035 MW since more wind is available as evident from the wind turbine output in the Fig. 7(a). Consequently, the power requirements from conventional generators are also greatly reduced as shown in the Fig. 7(d) and 7(e).



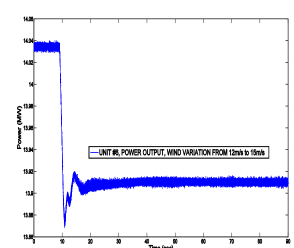


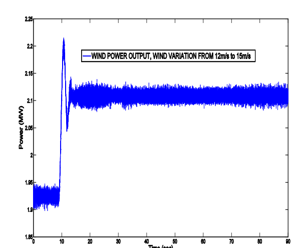
(a) (b)





(c) (d)





(e) (f)

Fig. 7. Response of wind speed variation (a) BESS P_{out}, (b) frequency, (c) voltage, (d) Unit #5 P_{out}, (e) Unit #6 P_{out}, and (f) wind P_{out}

D. Case IV

The main results obtained with a sudden load change are presented in the next figures. The load was varied from 6.01 MW to 8.01 MW, while the simulation is running, in order to simulate an increase in load demand as shown in Fig. 8 (d). The BESS ensures that the frequency and voltage remain within threshold limits of the power system during islanding operation as evident from the Fig. 8(b) and 8(c). Also, it is observed that the BESS increased its output power from 0.045 MW to 0.105 MW since there was a 2 MW shortfall in electrical power as evident from the Fig. 8(a). The difference was covered by the two thermal units, as shown in the Fig. 8(e) and 8(f).

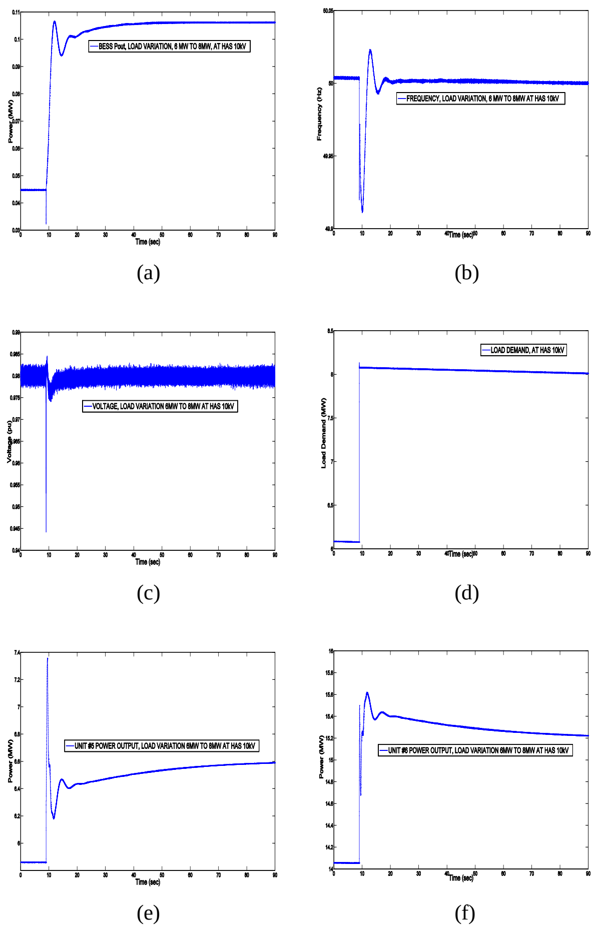


Fig. 8. Response of load variation (a) BESS P_{out}, (b) frequency, (c) voltage, (d) load demand (e) Unit #5 P_{out}, and (f) Unit #6 P_{out}

V. Conclusions

In this paper, a coordinated control scheme of the BESS and the power plants for stabilizing frequency under high wind penetration has been proposed. The BESS is designed to provide frequency support as a fast-acting primary control, and the CJLFC acts as a supplementary to help maintaining the constant frequency and voltage under islanding operation mode. The case study results with the Bornholm power system including aggregated WPP model and the BESS show that the proposed control scheme can respond very fast and ensure that the frequency remains within threshold limits of the power system. Clearly, it is observed that using only small amount of the BESS can improve the system response and the secondary regulation control can reduce the consumption of the stored energy of BESS without degrading the control performance. Hence, the results indicate the efficiency of the BESS for real-time applications and its suitability for the real power system case considered. In addition, the simulation results presented in this paper can quantify BESS performance both in EMS for real-time operation and in power system planning for future renewable energy resource connections. However, there are a number of challenges that require further improvement as future work. These are concerned with a dedicated state of charge (SOC) control scheme, the use of high time resolution wind data, coordination control strategies, and the controller optimization. Specially, the current BESS model can take energy from the grid when the frequency is too high and return that energy to the grid when the frequency begins to sag. The current implementation can provide a few minutes of energy, but overall grid management, including shifting peak loads, and supporting renewables, will require longer durations of storage and therefore re-engineering of conventional storage systems to handle greater energy/power ratios. The outcome of such optimization is a smart charge and discharge schedule for the BESS.

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